

6G Radio Technology Project Terminal-Cooperative MIMO Technology WG

September 30, 2025

Part I

Research Trends in Terminal-Cooperative Technology

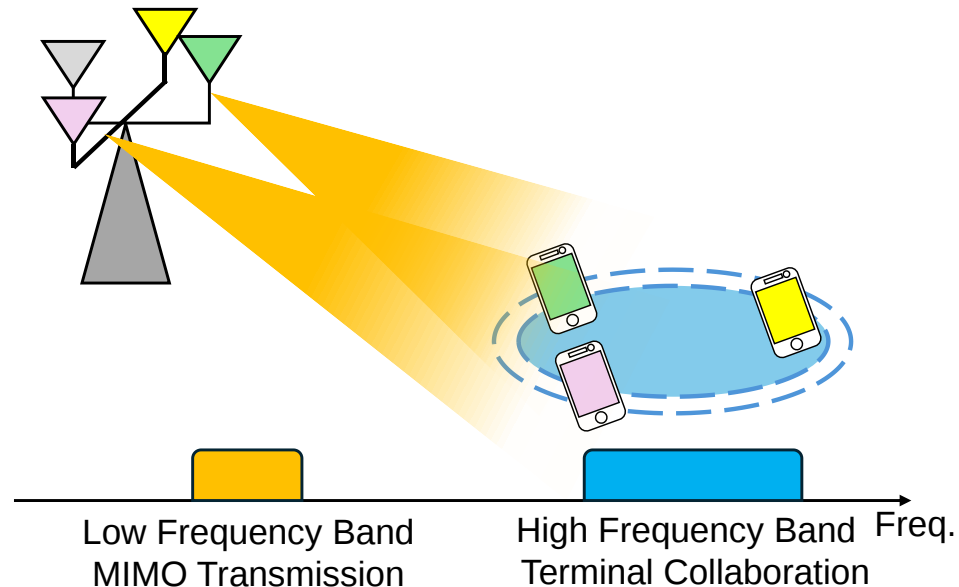
Terminal-cooperative technology involves multiple terminals collaborating in the Sub-6 band with longer transmission distances, while exchanging transmit and received signals between terminals in the millimeter-wave or terahertz bands with wider frequency bandwidths. The following three forms are considered as standard models.

1. Downlink Terminal Collaborative MIMO Signal Reception
2. Uplink Terminal Collaborative MIMO Signal Transmission
3. Uplink Terminal Collaborative Beamforming Signal Transmission

To highlight the importance of joint efforts, we use the term *collaborate* as the principal expression in the following parts.

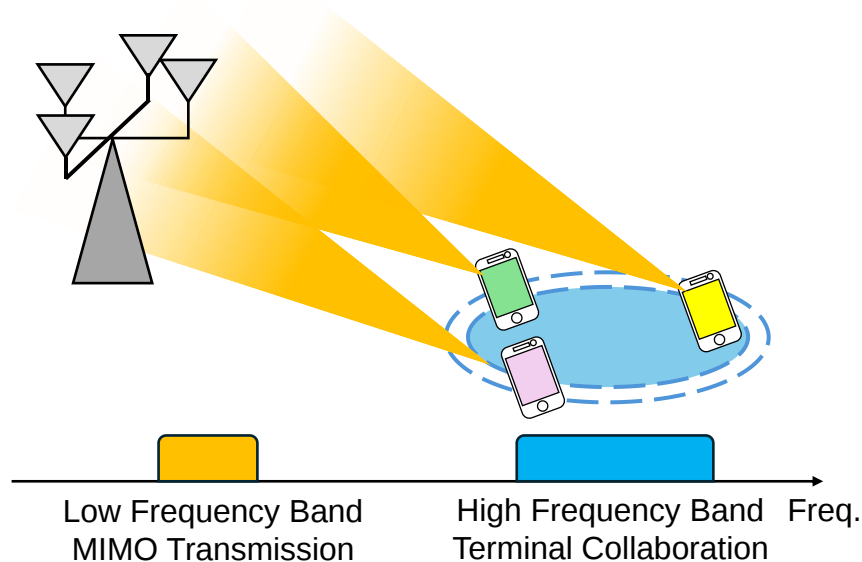
Downlink Terminal Collaborative MIMO Signal Reception

A model diagram of downlink terminal collaborative multi-input multi-output (MIMO) signal reception is shown below. In this model, the base station simultaneously transmits signals from multiple antennas to each terminal in the low-frequency band. Each terminal receives these signals and exchanges them in the high-frequency band. They work as virtual antenna elements and carry out MIMO signal detection.



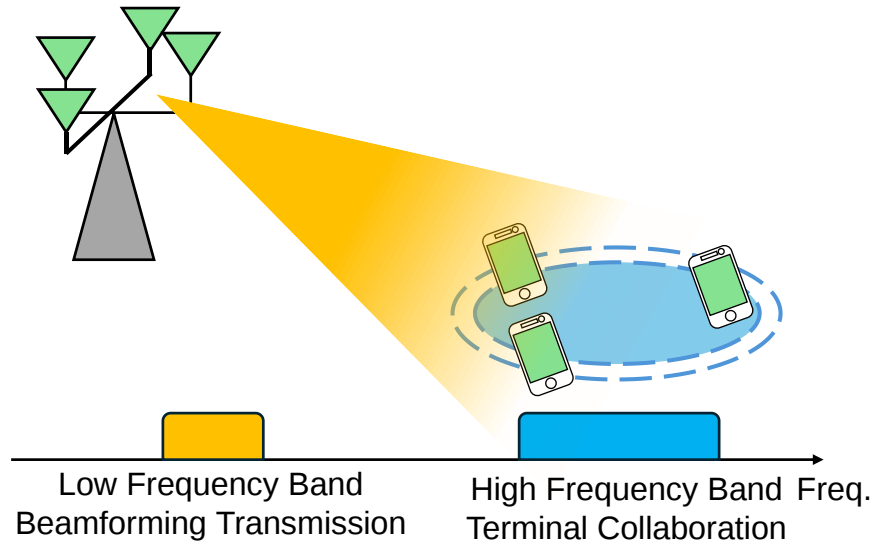
Uplink Terminal Collaborative MIMO Signal Transmission

A model diagram of uplink terminal collaborative MIMO signal transmission is shown in below. In this model, terminals first exchange signals they are going to transmit with each other in the high-frequency band. It is also possible for a specific terminal to request another terminal to transmit a signal on its behalf. In the low-frequency band, multiple terminals simultaneously transmit signals to the base station. The base station receives the signals and performs MIMO signal detection.



Uplink Terminal Collaborative Beamforming Signal Transmission

A model diagram of uplink terminal collaborative beamforming (BF) signal transmission is shown below. In this model, a specific terminal assigned to a frequency resource requests the other terminals to transmit a signal on its behalf. In the low-frequency band, multiple terminals simultaneously transmit the signal to the base station. In this case, phase adjustment is applied on the transmit signal so that the signal phases are coherently received at the base station. The base station receives and demodulates the signals.



Technical Issues

- I. Common Technical Issues
 - I. Collaborative Processing (Grouping of Devices and Assistants)
 - II. Wireless Security
- II. Technical Issues in Downlink Terminal Collaborative MIMO Signal Reception
 - I. Access Control
 - II. Terminal Grouping
- III. Technical Issues in Uplink Terminal Collaborative MIMO Signal Transmission
 - I. High-Capacity Data Transmission
- IV. Technical Issues in Uplink Terminal Collaborative Beamforming Signal Transmission.
 - I. Terminal Grouping
 - II. Signal Transfer Processing

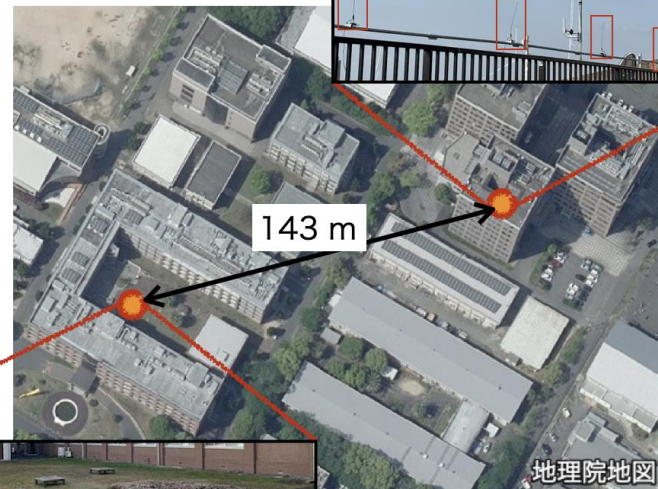
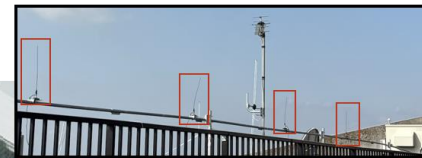
Part II

Field Trial of Terminal-Collaborated MIMO Reception

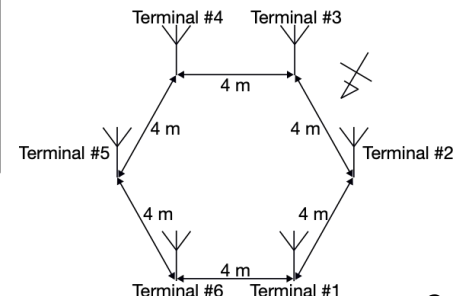
Collaboration with NTT AS

- Four-stream transmission in UHF band
 - 427.2MHz TX from rooftop of 8-story building
 - Received in the courtyard 143 m away
 - Six 1-antenna terminals move slowly around the circumference
 - Obtain RSSI, BER, etc. and record received signal waveforms
- Adaptive collaboration scheme on improved performance
 - Helper terminal that provides the received signal (H)
 - Decision terminal that decides from the collected received signal (D)
 - If the reliability is low, the judgment results of other decision terminals are acquired
 - If the confidence level is still low, D becomes H (H/D)

BS antennas



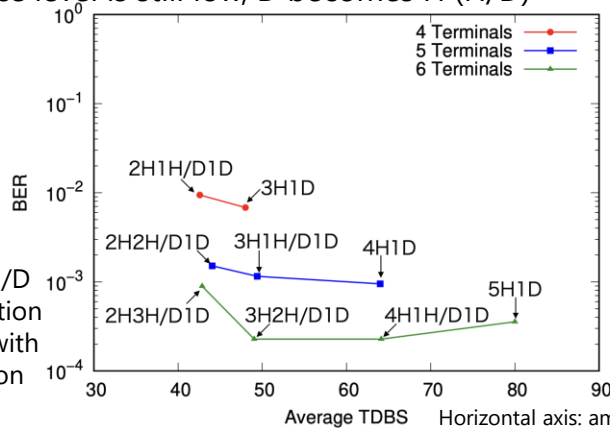
Terminal antennas



Each curve has a fixed total number of terminals

2H starts with overloaded MIMO, thus degrading performance

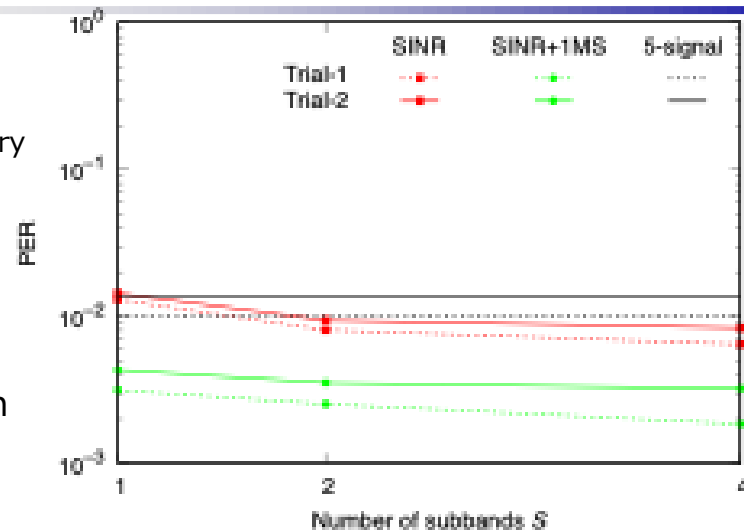
Increasing the number of H/D terminals in a 3H configuration can improve performance with little increase in collaboration traffic



On Demand Extra Helper Terminal Scheme

Collaboration with NTT DOCOMO

- Transmitting from a UHF 4-stream base station and receiving at 6 terminals
 - 427.2 MHz specific experimental test station, installed on an 8-story rooftop
 - Same setup as before slide
- Effect of improving performance by adding helpers as needed
 - Attempt decoding of a 4-stream transmitted signal with 4 terminals in collaboration
 - 4 terminals in this case are decided by SINR calculated from the MIMO channel matrix
 - Add helpers as needed based on the likelihood information when obtaining decoding results
 - Decoding is performed with 5 terminals in collaboration
 - The collaborating terminals are selected for each subband
 - Helpers to be added are common for all subbands



Received signal waveforms obtained in transmission experiments are used. 2 types: Trial-1 and Trial-2

The horizontal axis indicates the number of subband divisions in the signal bandwidth. Increasing the number of subbands improves the performance.

The proposed SINR+1MS scheme can significantly improve the performance compared to the SINR scheme and the scheme with fixed 5-terminal collaboration scheme.

Filtering-and-Forward (FF) Collaborative Relaying for Higher Spectrum Efficiency

Background & Objectives

- Higher spectrum efficiency is really needed in the next generation cellular system.
- While collaborative relaying achieves high transmission performance, the spectrum efficiency depends on relaying configuration.
- We propose a new collaborative relaying configuration that achieves higher spectrum efficiency.

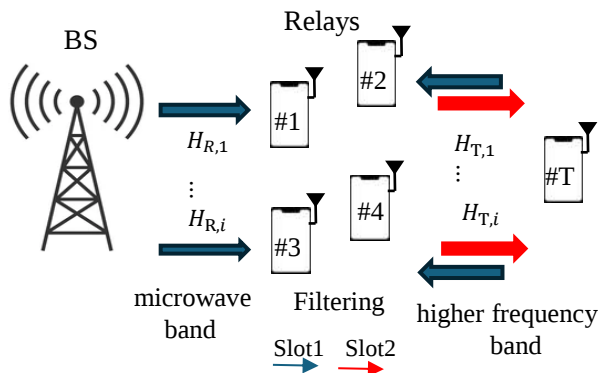


Fig.1 Configuration of FF collaborative Relaying

Proposed Configuration

(A) Relaying in 2-slots

- A BS and a destination terminal send their packets simultaneously in microwave and higher frequency bands for channel estimation, respectively.
- All the selected relays apply filtering signals sent from the base station in the frequency domain, and forward the signal for the destination as shown in Fig.1.

(B) Distributed Relay selection

- Every relay estimates the SNR in the channel from the BS to the destination via only the own relay, and transmits the signal if the SNR is bigger than the threshold.

Results

- The collaborative relaying makes possible in two slots despite of the number of the relays.
- As is shown in the right figures, the proposed relay selection achieves superior performance despite of the number of the candidate relays.

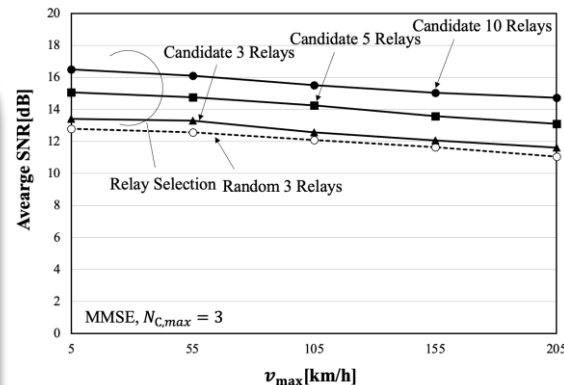


Fig.2 theoretical relay selection in the proposed relaying

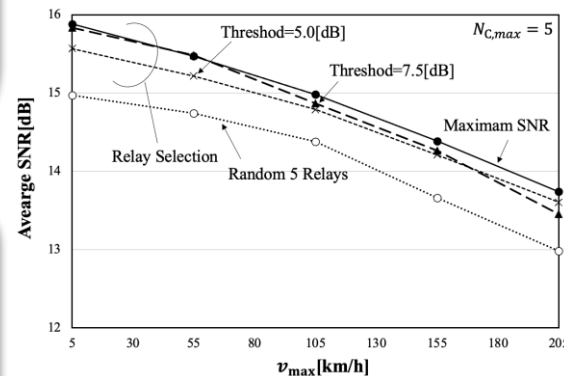
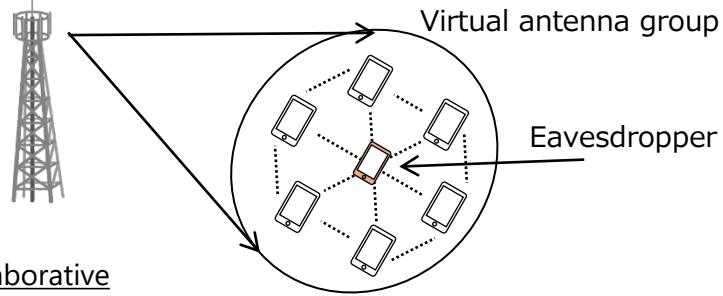


Fig.3 the SNR performance of the proposed relay selection

Physical-Layer Group Security in Terminal Collaborative Communication System

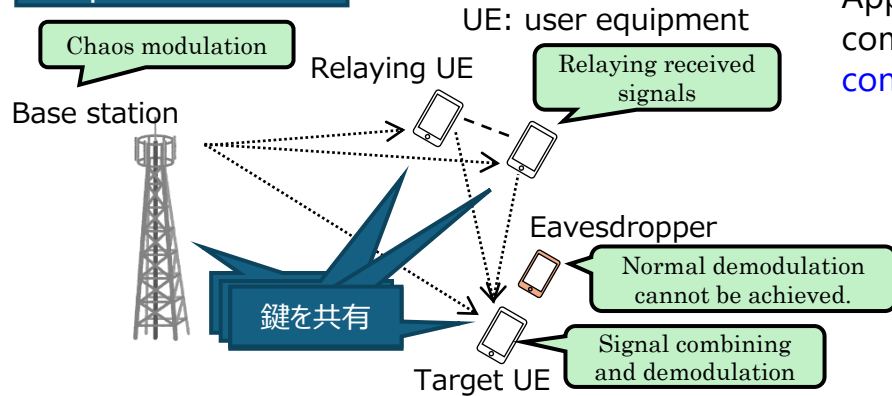
Objective

Base station



Terminal collaborative communication system between Terminals (with eavesdroppers)

Proposed method



Proposed downlink terminal collaborative communication system

- A transmission method that ensures group security even if an eavesdropper exists in the virtual antenna group is developed in terminal collaborative communication systems.
- By applying an encrypted modulation and a cooperative relay transmission schemes to the system, the information transmission performance as well as the physical layer security is improved.

Applying radio wave encryption modulation using chaos to obtain communication **channel coding effect** and **physical layer confidentiality**.

- A common key signal is shared within a group, assuming ID and pre-authentication, etc.
 - Base station transmits the signal to the target UE with chaos encrypted modulation in sub-6 bands.
 - Relaying UEs relay the received signal from base station in the millimeter-wave band.
 - Target UE combines the received signals from base station and relaying UEs, and demodulates them by maximum likelihood sequence estimation using a common key.
- ↓
- The group security and quality improvement are achieved by channel coding and the physical layer-encryption effects of chaos modulation, and the diversity effect of cooperative relay transmission.

Study Items: Safety evaluation of group security, transmission performance improvement, application to uplink transmission, common key signal sharing methods and delivery costs

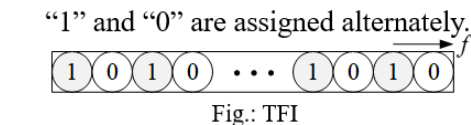
Phase Noise Compensation with Time Window Averaging for CTFI-OFDM

□ Aim:

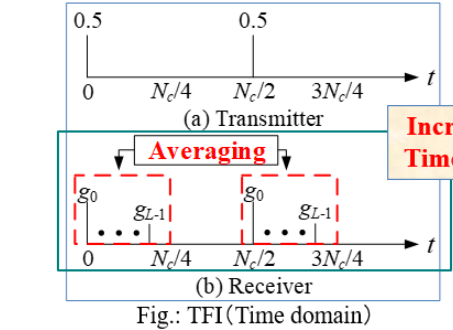
- OFDM subcarriers are assigned in a narrow bandwidth and are affected by the phase noise (PN) due to phase shift of local oscillator.
- The effect of PN is significant in a high-frequency band, and it also affects terminal coordination.
- The proposed method compensates the PN by the time window averaging (TWA) of pilot signal based on complex time frequency interferometry (CTFI).

□ Proposed method:

□ TFI:



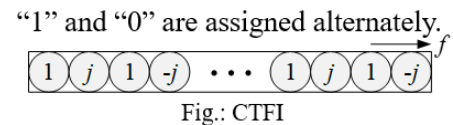
● Channel estimation (TFI):



- Phase noise: $\theta_i = \theta_{i-1} + w$, where w is based on Gaussian distribution.
 $\Rightarrow$ TW averaging $\Rightarrow$ Improvement of CSI

- $|(CIR \text{ bef. TWA}) - (CIR \text{ aft. TWA})| = \text{Magnitude of PN} \Rightarrow \text{Weight of MMSE}$

□ CTFI:



● Channel estimation (CTFI):

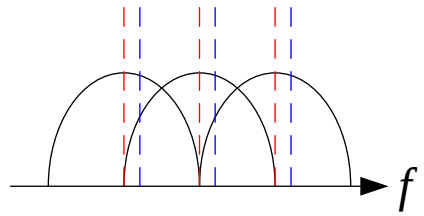
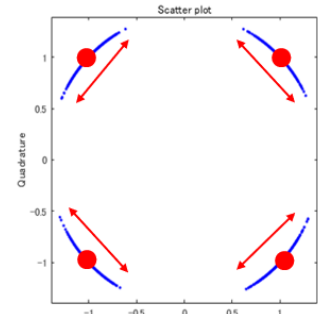
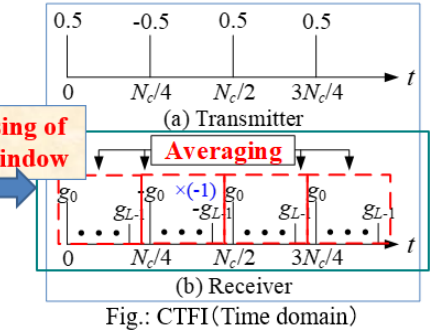


Fig.: Influence of PN

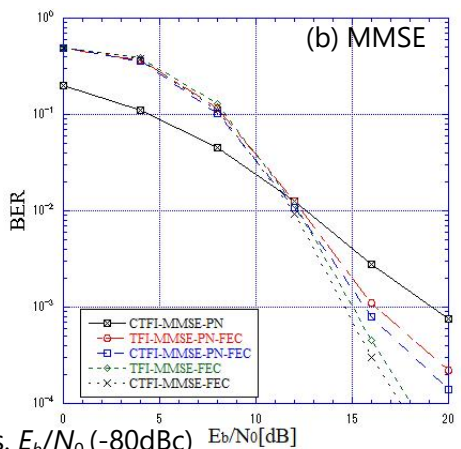
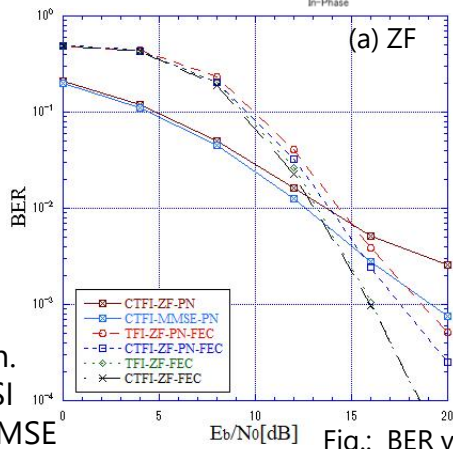


Fig.: BER vs. E_b/N_0 (-80dBc)

[1] S. Okamoto, et al., "Phase Noise Compensation with Time Window Averaging for WHT-CTFI-OFDM," Proc. IEEEGCC2024, pp. 1392-1393, Oct. 2024.

[2] S. Okamoto, et al., "Phase Noise Compensation with Time Window Averaging for Hadamard Spreading CTFI-OFDM," IEICE Tech. Rep., CS2024-10, pp. 13-14, July 2024.

Cooperative Positioning Techniques with User-terminal Collaboration Over Higher-frequency-bands

- ❑ **Terminal-collaborative virtual MIMO techniques** has been studied, where multiple nearby terminals cooperate in transmission and reception processing.
- ❑ By using terminal-collaboration techniques, it is expected to improve not only communication performance but also **positioning accuracy**.
- ❑ In this work, an enhanced cooperative positioning scheme is investigated, where each user terminal information is shared among users through direct inter-user communication at a **higher frequency band**.

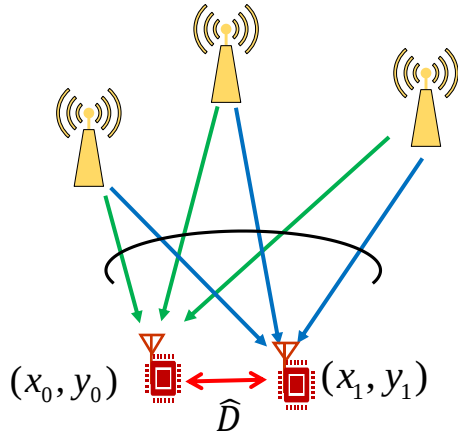


Fig1: Basic concept of cooperative positioning with nearby user-terminal collaboration

- The distance between 2 users can be estimated by $D = \sqrt{(x_0 - x_1)^2 + (y_0 - y_1)^2}$, while it can be also estimated by RSS measurement of direct link, where estimated distance by direct link is $\hat{D}$.
- Positioning accuracy can be improved by finding a solution that minimizes the weighted sum-of-squares errors of inter-user distance, i.e., $|D - \hat{D}|^2$.
- Simulation results show that user terminal collaboration significantly improves positioning accuracy in various evaluation scenarios ^{[1][2]}.

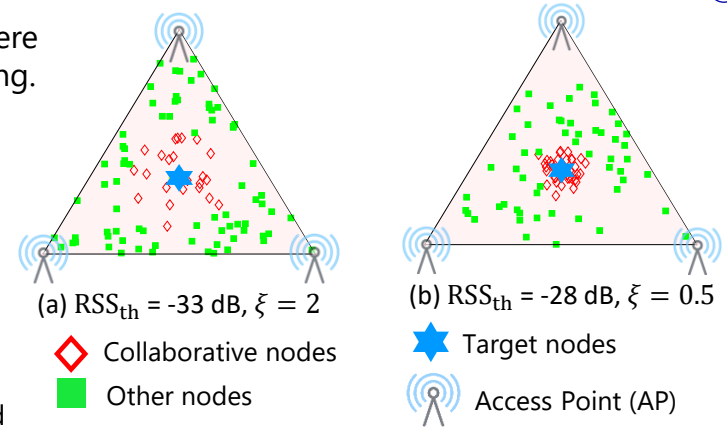


Fig. 2: AP positions and user distributions.

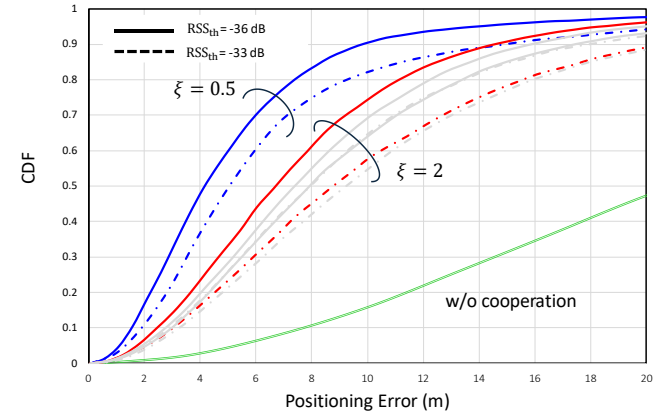


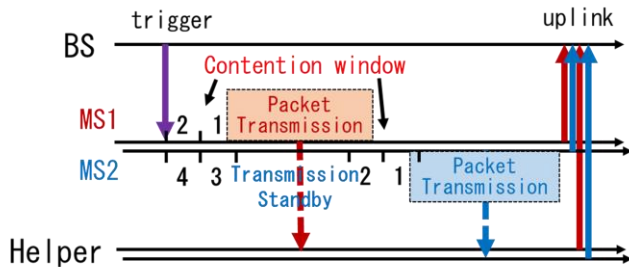
Fig. 3: CDF of positioning errors in case with and without cooperative positioning

[1] Z. Li, et al., "Performance Evaluation of Cooperative Positioning with User-Terminal Collaboration," Prof. JAC-ECC2023, Dec. 2023.

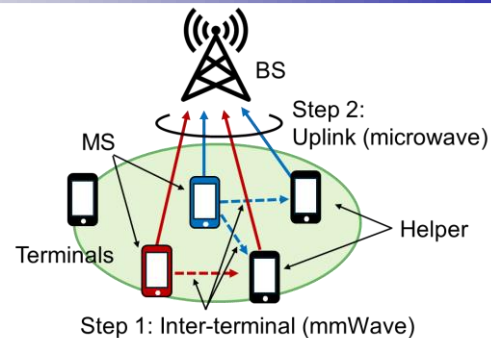
[2] Z. Li, et al., "Performance of RSS-Based Indoor Cooperative Positioning with Weighted User-Terminal Collaboration," Prof. JAC-ECC2024, Dec. 2024

Access Control for Terminal Collaborative Communication System

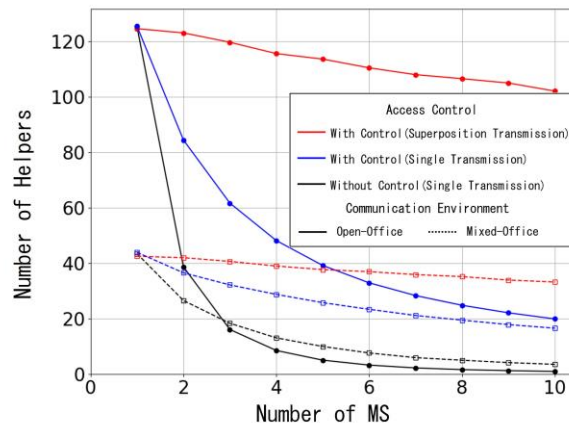
- Uplink terminal collaborative communication system
 - Uplink: sub-6 band, Inter-terminal: mmWave band
- Inter-terminal communication
 - MS broadcasts its data to terminals
 - Terminals that successively receive data becomes Helpers
- Issues and results
 - Evaluation of number of helpers, which affect uplink capacity
 - Performance evaluation considering mmWave indoor propagation model
 - Introduction of access control avoiding interferences



Timing chart of access control



Uplink terminal collaborative communication system



Number of helpers in mmWave indoor environment^[1]

[1] Y. Li, et al., "Evaluation of access control mechanisms within inter-terminal cooperation...", IEICE ICETC, 2024.

Grouping Scheme in Terminal Collaborative MIMO

• Downlink Terminal Collaborative MIMO Reception

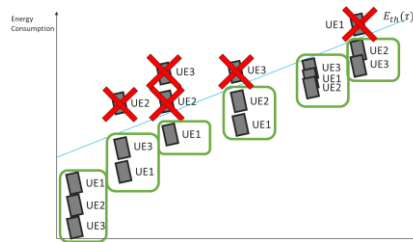
- Grouping based on instantaneous throughput
⇒ Throughput improvement by a factor of 1.13

• Uplink Terminal Collaborative Beamforming Transmission

- Set thresholds on number of assistant UEs in group
⇒ Reduce assist probability of cell-site UE by 1/5 with nearly the same throughput

• Grouping based on Cumulative Energy Consumption

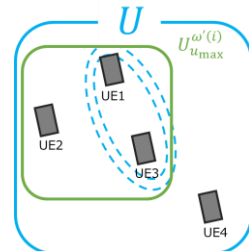
- Set thresholds on cumulative energy consumption of each terminal
- Threshold based on subframe index
 - Collaboration if energy consumption is less than threshold
 - Leave group if energy consumption is more than threshold
 - Rejoin group if threshold exceeds energy consumption



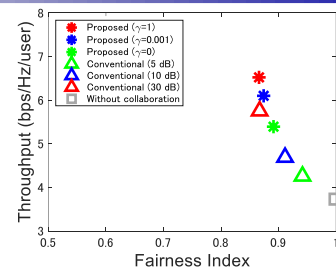
Threshold based on subframe index

Index m	Subgroup	Th	FI
1	(UE1, UE2, UE3)	$\sum T_u^{(1)}(t)$	$R_{ins}^{(1)}$
2	(UE1, UE2), UE3	$\sum T_u^{(2)}(t)$	$R_{ins}^{(2)}$
3	(UE2, UE3), UE1	$\sum T_u^{(3)}(t)$	$R_{ins}^{(3)}$
4	(UE3, UE1), UE2	$\sum T_u^{(4)}(t)$	$R_{ins}^{(4)}$
5	UE1, UE2, UE3	$\sum T_u^{(5)}(t)$	$R_{ins}^{(5)}$

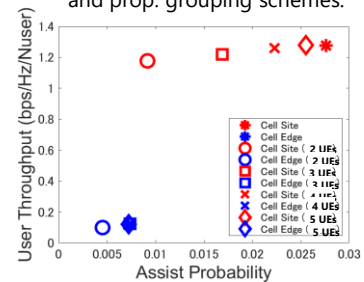
Grouping based on instantaneous throughput.



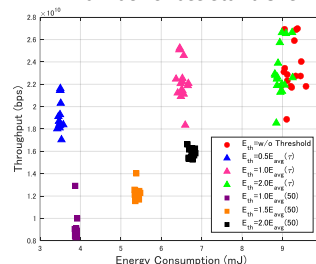
Grouping with limited number of assistant UEs



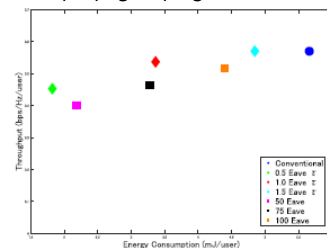
Throughput vs. fairness with conv. and prop. grouping schemes.



Assist probability with conv. and prop. grouping schemes.



Throughput vs. energy consumption with thresholds based on subframe index and fixed thresholds.



Throughput vs. energy consumption with thresholds based on subframe index and fixed thresholds.

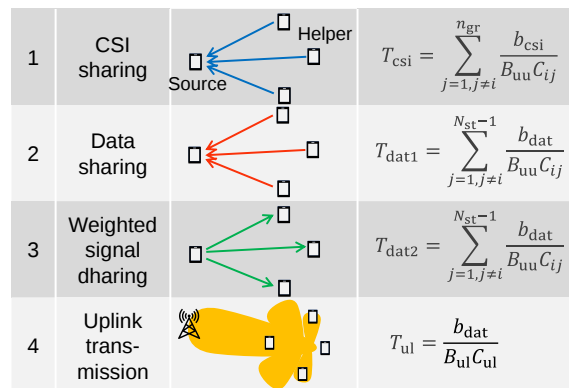
Grouping Scheme in Collaborative MIMO (2)

Objective

- Validate the effectiveness of collaboration while considering the overhead for information sharing
- Organize multiple groups to maximize throughput while targeting considering terminals

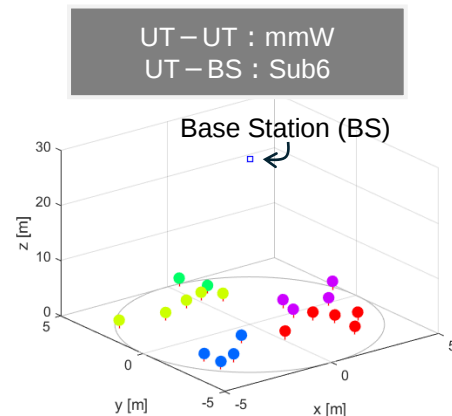
Research Direction

- Formalization of uplink cooperative MIMO transmission considering overhead
- Grouping via clustering (k-means)
- Selection of collaboration terminals (UTs), resource / fairness management considering channel conditions between UTs and BS

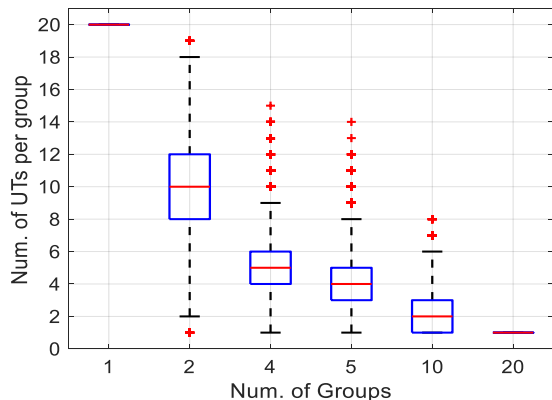


Flow of collab. MIMO uplink

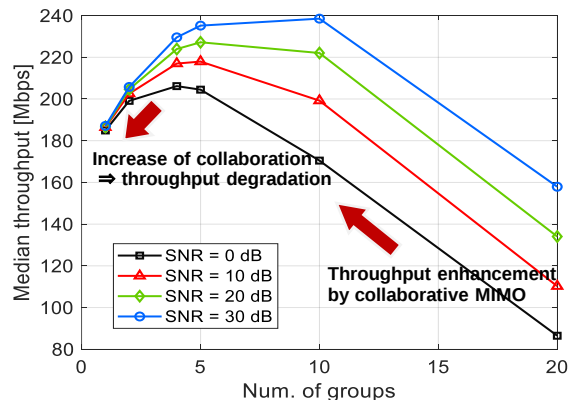
$$TP = \frac{N_{st} b_{dat}}{T_{csi} + T_{dat1} + T_{dat2} + T_{ul}}$$



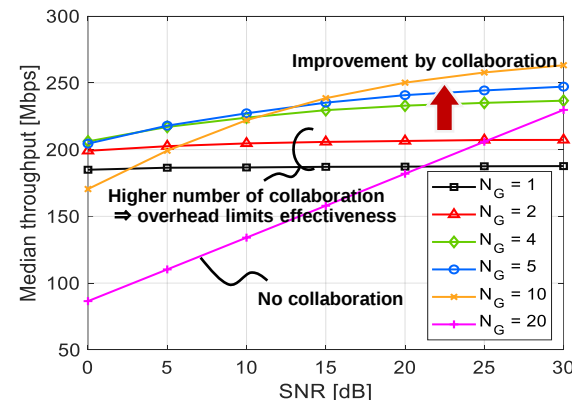
Example of clustering



Number of UEs per Group (Clustering 20 UTs)



Median Throughput when Grouping 20 Terminal



Median Throughput vs. UT-BS SNR

Virtualized Terminal Technology

- Increasing the number of antennas virtually by wearable devices with mmW-band antennas and connecting them to the user terminal via a terahertz ultra-wideband link.

